EVALUATION OF LABORATORY TECHNIQUES FOR ALUM DOSE SELECTION FOR DIRECT FILTRATION

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CERTIFICATE

Certified that the work presented in this thesis entitled "Evaluation of Laboratory Techniques for Alum Dose Selection for Direct Filtration" has been carried out by Shri V. Kandasamy under my supervision and it has not been submitted elsewhere for a degree.

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ABSTRACT

A study was conducted to evaluate two recently developed laboratory techniques for alum dose selection for direct filtration. For a raw water turbidity range of 10-30 NTU, suitable for direct filtration, both Hudson's modified jar test for direct filtration as well as Ives' filterability number test were found effective in predicting alum doses for both single- and dual-media direct filtration. The predicted doses were 80-85 percent of those found optimum from bench-scale column studies at a filtration rate of 9.8 $m^3/m^2/hr$ (4 gpm/sq.ft). Hudson's modified jar test for direct filtration could also predict well the filter column effluent turbidity. On the other hand, the conventional jar test (coagulation-settling) was found to be rather insensitive for predicting direct filtration alum doses. Further experiments including other relevant variables, viz., filtration rate, media size and flash mix durations are recommended.

1. INTRODUCTION

Water is probably the most important natural resource in the world, since without it life cannot exist. It is required for a variety of purposes such as domestic, industrial, agricultural and recreational uses. Unlike many other raw materials there is no other substitute for water in many of its uses. A reliable supply of water is an essential prerequisite for the development of communities. The growing population and industrial developments demand ever-increasing supplies of water. Though seven percent of earth's mass is made up of water, only an insignificant 0.7 percent of earth's water occurs in freshwater lakes and rivers, in accessible aquifers and in atmosphere. The remaining major portion of water is found as saline ocean water and as polar ice caps. The uneven distribution of this limited sources of water and population, have led to the acute problem of water shortage.

Because of the essential role played by water in supporting human life it also has, if contaminated, great potential for transmitting a wide variety of diseases and illnesses. In the developed countries water-related diseases are rare, due essentially to the presence of efficient water treatment and wastewater disposal systems. However, in the developing countries the toll of water-related disease is frightening in its extent. A recent WHO survey has highlightened the following facts:

> Each day some 30,000 people die from water related diseases. In the developing countries 80 percent of all the illness is water-related.

> A quarter of children born in the developing countries will have died before the age of five, the great majority from water-related diseases.

A survey in 1975 found that 80 percent of the world's rural population and 23 percent of urban population have no reasonable access to a safe water supply (Tebbutt, 1983). So the responsibilities of the public health engineer start with the development of water source to provide an ample supply of water and providing necessary treatment to make the water potable and palatable.

Water science and technology is an interdisciplinary topic involving the application of biological, chemical and physical principles in association with engineering techniques. Viewing the treatment process from this angle, water as well as wastewater treatment systems can be grouped under three main classes.

1. Physical process which depend essentially on physical properties of the impurities, e.g., particle size, specific gravity, viscosity, etc. Typical examples of this type of process are screening, sedimentation, filtration, and gas transfer.
2. Chemical process which depend on the chemical properties of an impurity or which utilize the chemical properties of the added reagents. Examples of this type are coagulation, precipitation, and ion exchange.
3. Biological process which utilize biochemical reactions to remove soluble or colloidal impurities, usually organics. Aerobic biological process include biological filtration and activated sludge. Anaerobic

oxidation processes are used for stabilization of organic sludges and high strength organic wastes.

Modern technology provides the engineer with a choice of treatment methods that can produce virtually any desired quality of water from any given source, the limiting factor being economy rather than technique. Especially countries like ours, which have limited financial resources, the selection of source of water as well as the selection and application of appropriate technology are vital. For example, if an underground source with safe levels of chemical constituents is accessible, chlorination may be the only needed treatment. But if the source is a surface one, the engineer may go for a conventional process chain which includes coagulation, sedimentation, filtration and disinfection.

More recently, it has been shown that when a relatively high quality surface water supply is available, direct filtration, a process chain without sedimentation prior to filtration, may be successfully employed, utilizing high hydraulic loading rates, to assure high-quality finished water with large savings in capital and running costs. So this scheme seems to be a potentially attractive alternae technology for utilization in the developing countries like ours.

The present study was directed towards one important stage of direct filtration, namely, selection of coagulant dose. At present the treatment plant personnel have got only the conventional jar testing, which may not be fully dependable in the case of direct filtration, as the only means of controlling the pretreatment stage. So two other

available laboratory techniques, namely, the Hudson's modified jar test for direct filtration (Wagner and Hudson, 1982) and Ives' filterability number test (Ives, 1978) along with the conventional jar test, were evaluated in the present study. The alum doses obtained using these techniques were compared with those found suitable from bench-scale column studies.

2. PRESENT STATE OF KNOWLEDGE

2.1. Development of the Concept of Direct Filtration

Direct filtration is not a new idea. Back in the early 1900s, during the conversion period from slow sand to rapid sand filters, attempts were made to explore the direct filtration mode. These attempts failed because of the rapid clogging of the fine-to-coarse single-media filter beds. The development of coarse-to-fine dual-media and mixed media filters and more insight into the mechanisms of coagulation have increased the prospect of direct filtration process as a candidate water treatment process for a wide variety of raw waters (Culp, 1977).

The second factor which has revived the interest in direct filtration is the 1 NTU limit, lowered from the 5 NTU limit set by the U.S. Public Health Service's 1962 Drinking Water Standards. A large number of small communities in the U.S. which were earlier having little or no treatment other than disinfection, have now adopted direct filtration to meet with the new turbidity limit with reasonable cost (McCormic and King, 1982).

The new trend to tailor the design of the plant to the characteristics of the raw water that is to be treated, and the emergence of polymers as coagulants in water treatment, have strengthened the recent interest in direct filtration.

2.2. Theoretical Considerations

Direct filtration is a water treatment scheme that does not include separate inplant sedimentation. Two major

unit operations are involved in this process, viz., destabilization of particles by coagulant in the rapid mixing unit with or without subsequent flocculation, and removal of the destabilized agglomerated microflocs by filtration.

In conventional treatment, attempts are made to produce a settleable floc in the coagulation-flocculation process and to remove the floc in the settling basins. The filter is used primarily as a polishing unit. In direct filtration, a filterable floc rather than a settleable floc is the basic main aspect, and all the solids - those naturally occurring in the raw water and those added as part of the treatment process - are removed from the water by the filter unit.

Following proper mixing of the coagulant with raw water, a number of complex reactions take place with colloidal turbidity and color According to Stumm and Morgan (1962), the action of conventional coagulants (aluminum and iron salts) is primarily due to their hydrolysates. These are polymer chains with good adsorption properties that can form structures as a result of bonding. Coagulation with the aid of these materials,takes place in two steps: neutralization of the particles' negative charge by the positive hydroxide, and formation of flocs by bridging between the particles as a result of the polymer chain adsorption. The theoretical considerations of particular interest to direct filtration are focussed by Amirtharajahand Mills (1980), who reviewed the literature on destabilization of colloids by alum treatment. Destabilization was established by measurement of colloid charges before and after alum treatment.

No polymers were used. The published data, when plotted on the aluminum solubility domain diagram, show a zone of restabilization from about pH 4.7 to 6.7 and alum dosage levels from 1.5 to 30 mg/l. At dosage levels below 3.0 mg/l there is a zone in which adsorption-destabilization occurs, but sweep floc does not take place. In the destabilization zone, excellent coagulation occurs, but flocculation does not take place. They suggest that the use of the adsorption-destabilization process should be well-suited to direct filtration. These coagulation reactions take place within few seconds. In direct filtration, as the elimination of the settling step is desired, the conventional means of flocculation also can be eliminated. The water containing the destabilized particles can be taken directly to a granular filter where contact flocculation takes place as a part of the filtration process at a greatly accelerated rate because of the tremendous number of opportunities for contact afforded in the passage of the water through the granular bed.

The difference in the objective of coagulation step is unlikely to make the mechanism of removal in direct filter units differ from that of sedimentation-filtration units. Adin et al. (1979) gave a comprehensive review of filtration theory. The removal process consists of two steps - a transport step and an attachment step. Particle transport is basically a physical-hydraulic process which transports the particle from their carrying stream to the vicinity of the grain surface where attachment forces can be effective. Four main physical mechanisms are gravity settling in the

pore spaces, direct interception, diffusion due to Brownian motion, and rotation caused by hydrodynamic regime and angular shape of the particle. This step has been considered, as such, as a relatively insignificant step in filter design since the existing mechanisms are sufficient to do their job even for particles that have minimum transport ability.

Particle attachment is a physicochemical process which may be classified according to two models. The classic 'double-layer' model is based on an interaction between the electrostatic repulsive forces and van der Waals attractive forces. The 'bridging-model' explains effects resulting from chemical bonding and bridging of the suspension particles and the medium through their interaction with the flocculant. According to Agrawal (1966), electrokinetic forces by themselves are capable of transporting and attaching suspended particles.

A third step, 'a detachment step', was suggested by Mintz (1964). It states that retained particles are being detached as long as new particles are being supplied. The pores of the filter bed gradually fill with floc as particles are sheared off the surfaces of filter grains. As filter run progresses, the upper pores of the filter cannot retain any more floc, and the particle move down into the filter to find resting place. Finally, either turbidity breakthrough or excessive head loss across the bed occurs, indicating the need for back wash. The success of direct filter unit depends on the total amount of solids, their strength in attachment on the filter grains and available storage space.

2.3. Factors Affecting Direct Filtration

2.3.1. Raw Water Quality

Generally, natural waters with low color and turbidity, have proved to be the most suitable for direct filtration. The AWWA Filtration Committee (1980), on the basis of its worldwide survey of pilot and operating plants using direct filtration process, came out with the following observations:

1. Color exceeding 30-40 Hazen units or turbidity greater than 15 FTU (Formazin Turbidity Units) on a continuing basis could be expected to give problems.
2. In the absence of dual-media filters, the filter-clogging varieties of diatoms can affect the process.
3. Low temperatures may lead to inadequate chemical reactions. Higher raw water pH than 5 and 7, in the case of alum, may result in after floc formation and certain interference in the treatment process.

Kawamura (1975) suggested that when the average raw water turbidity exceeds about 10 NTU (Nephelometric Turbidity Units), direct filtration usually is not cost effective. McCormic and King (1982) recommended the following raw water characteristics for direct filtration: turbidity, 0-10 NTU; colour, 0-15 APHA units; algae (clump count), 0-100 units/mL. Hutchison (1976) found that with the help of nonionic polymers as filter aid, turbidity levels upto 175 FTU could be treated. Culp (1977), however, proposed much less stringent raw water quality limits. He suggested that direct

filtration may be an attractive option under any of the following conditions:

(a) Color and turbidity are both less than 25 units.

(b) Maximum turbidity is less than 200 NTU and color being very low.

(c) Maximum color is less than 100 APHA units and turbidity being very low.

The upper limits for various water quality characteristics that can affect the process choice appear to vary with different waters. In addition, some techniques of operation can be designed to overcome the percluding raw water condition. Thus the above numerical values of raw water quality provide only a preliminary indication. Only the pilot plant tests can provide necessary information regarding the applicability of direct filtration for the prevailing raw water condition.

2.3.2. Coagulant Type and Dose

The initial unit process in direct filtration is colloid destabilization by chemical treatment in a rapid mix unit. The importance of this step to the overall success of direct filtration has been emphasized by several investigators (Culp, 1977; Hutchison and Foley, 1974; Tredgett, 1974; King and Amy, 1979; and Tate et al., 1977). According to Kawamura (1976), the choice of coagulant is important and aluminum salts are one of the most effective, economical, and foolproof coagulants in use today. Coagulation by aluminum salts is affected by salt concentration, pH, temperature, nature of solids, size of turbidity causing particles, mixing, and coagulant concentration. One problem

with the use of aluminum salts as a coagulant in direct filtration is early breakthrough of turbidity with increasing coagulant dosage (Hutchison, 1976). According to Kawamura (1976), the advantages of using polymers as primary coagulants include reduced sludge volumes, reduced coagulant dosages, improved sludge dewatering, lowered chemical residuals in the filtered water, and the diminished problems with pH and alkalinity adjustments; polymers are also nontoxic. There may be some problem in using cationic polymers as primary coagulants in dual media filters from an efficiency standpoint. A low-turbidity water is difficult to coagulate with polymers due to particle scarcity (Weber, 1972). Hutchison (1976) observed this in his direct filtration studies that for low turbidity of <5 FTU, polymer dosage should be supplemented with a minimum amount of alum (2 mg/l). Polymers are used as coagulants, coagulant aids, and filter aids. Typically, cationic polymers are used as primary coagulants and coagulant aids, whereas nonionic and anionic polymers are used as coagulant aids and filter aids. A polymer is used as a filter aid in direct filtration to prevent turbidity breakthrough before terminal head loss is reached. Moreover they do not add extra solids load to the system. The general trend in U.S. is to use either aluminum or iron salts as coagulant with polyelectrolytes as coagulant aid.

The filter clogging is related directly to floc volume that is loaded onto the filter and the floc volume is related directly to coagulant dose. This direct proportionality of floc volume to coagulant dose was noted and

confirmed using alum by Hutchison and Foley (1974). Therefore, a low coagulant dose increases the chances of successful treatment by direct filtration. Wagner and Hudson (1982) came out with the following guidelines:

1. When the required coagulant dose is less than 6 to 7 mg/l with the addition of a small dose of polymer, the water is an excellent candidate for direct filtration.
2. If the required dose is more than 15 mg/l, the water is a doubtful candidate.
3. For doses between 6-7 mg/l and 15 mg/l, the potential of direct filtration must be evaluated case by case.

All these can be tempered by designing a filter with more storage that will take higher loads. The AWWA Filtration Committee (1980) found that majority of the plants treating raw water of the quality suitable for direct filtration, used coagulant dose in the 0-10 mg/l range. But significant number of plants (mainly industries) had coagulant dosages above this range. It also noticed that alum had been utilized with success at many installations. Hutchison (1976) suggested that cationic polyelectrolytes could reduce or completely replace alum with longer filter runs for raw water turbidity 5 NTU. He also noticed that alum alone could achieve excellent effluent quality when the dosage was 3.8 mg/l. He found ferric chloride as an attractive alternative to alum since similar performance was achieved at one third to one half dose. Adin et al. (1979) stated that, in general, polyelectrolytes have not proven to be as effective as alum for color removal. Monscvitz et al. (1978)

came out with a combination of alum and cationic polyelectrolyte in the ratio of 10:1 for overall best pilot plant performance from their direct filtration studies. Adin and Rebhun (1974), when studying high-rate contact flocculation, found that efficient filtration with alum alone was achieved only at filtration velocities of 5-10 m/hr and with media upto 0.6 mm grain size. For high rates and coarse media, they suggested the use of polyelectrolytes which cause strong attachment.

2.3.3. Rapid Mixing and Flocculation

No unique process can be said to define direct filtration mixing requirements. No definite trend in regard to mixing and flocculation energy, mode and time is observed from the available data, although the plants with fewest problems have good control of both the coagulation and flocculation processes (AWWA Filtration Committee Report, 1980).

The need for a slow mixing or flocculation basin in direct filtration has been a matter of disagreement. Culp (1977) reported that flocculation basins could be eliminated, with no subsequent effect on the filtration process. Adin and Rebhun (1974) investigated a scheme in which rapid mixing and flocculation as separate units were eliminated with good results. Adin et al. (1979) stated that it was unlikely that flocculation should be required or that the flocculant dosage needed would be affected by flocculation unless additional time was required for effective uniform mixing and interaction of chemicals with the particles.

Floc formation, it would seem, is not helpful unless it happens through the contact with the filter grains. But Monscvitz et al. (1978) found longer filter runs with more evenly distributed head loss with ~~lesser~~ coagulant dose in case of filtration with flocculation when compared with contact-flocculation. Treweek (1979) also observed that the flocculation basin was necessary to achieve the desired level of treatment.

The flocculation time for direct filtration has also been investigated by many investigators. Hutchison (1976) reported that flocculation times greater than 4.5 min increased the probability of turbidity breakthrough. It was believed that the flocs formed during the flocculation stage became progressively weaker due to constant collisions when the mixing time exceeded 4.5 min resulting in turbidity breakthrough at much lower head loss. Sweeney and Prendiville (1974) suggested that the flocculation time should be varied from 10 min during hot weather to 30 min during cold weather. Hutchison and Foley (1974) observed that flocculation times should be greater than 3.5 min to prevent after floc formation but less than 10 min to prevent turbidity breakthrough and rapid head loss accumulation. They also mentioned that with water temperature less than 3.3°C, flocculation duration greater than 10 min might be needed to prevent after floc formation. Tate et al. (1977) observed that increasing the flocculation time from 13 to 26 min for G of 100 sec^{-1} was not accompanied by improved water quality. On the whole, no definite trend is observed.

Hudson (1965) showed that the volume of flocs was larger for low agitation speeds than for high agitation speeds - the difference being as much as 25 fold. Hutchison (1976) studied a wide range of G from 20 to 300 sec^{-1} after a flash mix (G-500 sec^{-1}) for 1-2 min. The flocculation velocity gradient of 300 sec^{-1} appeared to create smaller flocs but promoted earlier breakthrough in the filter run, than when a flocculation G value of 20 sec^{-1} was used; flocculation G values 100 sec^{-1} and 20 sec^{-1} resulted in similar filter characteristics. Monscvitz et al. (1978) suggested the values of GT in the order of 25,000 to 50,000 for optimized filtration. He found that full scale plant performance was optimized when zeta potential of the pre-treated water was between 0 and +3 mV. With short detention time and mixing time of the full scale plant, a liquid alum dose of 22 mg/l was required to raise the raw water zeta potential from levels of -19 to -21, to 0 mV. As flocculation time was increased in jar tests, the alum dosage decreased to 8 mg/l liquid alum to produce a zeta potential of 0 mV. Wagner and Hudson (1982), in their bench-scale work, used a flash mix velocity gradient of about 500 sec^{-1} for about 30 sec. McCormic and King (1980) in their pilot filtration tests used flash mix G of 1290-1650 sec^{-1} for a duration of 3 min and flocculation G of 20-63 sec^{-1} for a duration of 28 min.

All these observations imply the need for more investigation in this area, namely, mixing requirement of direct filtration.

2.3.4. Filter Design Variables

2.3.4.1. Media

The AWWA Filtration Committee (1980) observed that most of direct filtration plants used dual-media filters, with many industrial and some municipal plants using mixed-media filters. Pilot studies and recently constructed plants had employed larger size anthracite media between 1 and 1.2 mm effective size. The use of larger size coal avoids short filter runs and consequent increased backwash requirement and variations in raw water quality. The sand layer is very important in maintaining low effluent turbidities. The sand in most of the plants was found to vary between 0.4 and 0.5 mm effective size. Many industries treating raw waters with turbidities upto 500 FTU and color upto 1000 Hazen units, were found to use a third layer of garnet sand with an effective size of 0.2-0.3 mm. Hutchison (1976) found that in the absence of diatoms, the best effective size of coal with regard to effluent quality, length of filter runs and floc distribution within the filter bed was near 1.05 mm; and in dual media filters, the effluent turbidity was not a function of the effective size of coal within the size range of 0.9 to 1.55 mm; the optimum head loss distribution for maximizing filter runs was approximately 75 percent for the coal and 25 percent for sand. Gadkari _et al_. (1980) when investigating the feasibility of using direct filtration process for the raw water of Bhatsai river near Bombay, found that there was no noticeable difference in the filter runs between coal capped

(coal: 1 to 1.2 mm size, depth: 15 cm, sand: e.s. 0.65 mm, u.c.: 1.3 and depth: 75 cm) and coarse sand filter at the turbidity range of 50 to 150 JTU. McCormic and King (1982) found that a filter media configuration of 51 cm of 1.3 mm e.s. coal and 25 cm of 0.45 mm e.s. silica sand was the most effective when all variables were taken into consideration. This configuration tested with alum as well as alum and polymer coagulation produced water of less than 1 NTU turbidity for run times of at least eight hr when the raw water colour and turbidity were less than 15 to 20 units. Adin *et al*. (1979) suggested that deep bed of coarse sand would yield filtrate quality as good as that of shallow depths of dual or triple media and these could be operated at high rates with simpler backwashing routines. The pilot plant studies for direct filtration by the Los Angles Department of Water and Power implied the same. Coarse media (2.0 mm) deep bed (2.4 m) filters and dual media (1.10 mm coal; 0.51 mm sand) shallow-bed (50.8 cm coal; 25.4 cm sand) filters were operated with proper chemical pretreatment at rates of 4.08, 8.14 and 12.2 mm/sec (6, 12 and 18 gpm/sq.ft) with equivalent performance (Adin *et al*., 1979).

2.3.4.2 Depth

The depth of the filter media is an important parameter; greater depth of coal allows more storage and longer filter run. But this advantage must be balanced against operational difficulties - need for increased filter box depth and increased water level above the media to avoid a negative head in the filter bed prior to

termination of filter run. The depths of coal ranged from 37.5 to 90 cm and sand from 20 to 30 cm (AWWA Filtration Committee Report, 1980).

2.3.4.3. Filtration Rate and Run

Early design of direct filtration process was based on a conservative 1.4 mm/sec (2 gpm/sq.ft) rate. But the survey of AWWA Filtration Committee (1980) found that the operating plant rates ranged from 0.7 to 4.1 mm/sec (1 to 6 gpm/sq.ft). At the lower rates many of the plants had filter runs upto 4 to 5 days. Many plants were operated at a constant rate rather than a declining rate. Wagner and Hudson (1982) successfully pilot-tested several waters for low dosage direct filtration at filtration rates of 3.5 to 10 mm/sec (5 to 15 gpm/sq.ft). The 840 mgd Prospect Water Treatment Plant in Sydney, Australia, the largest direct filtration facility in the world, was designed for a hydraulic loading rate of 5.4 gpm/sq.ft with minimum predicted run of 15 hr at highest raw water turbidity levels (Walder et al., 1975). The preliminary subcommittee report, "Survey of Direct Filtration Practice" presented in 1976, stated that the average run for all the plants varied from a range of 5-8 hr to a range of 72-100 hr. Filter runs were terminated when the head loss reached 1-2 m or when filter effluent turbidity reached 0.1-1.0 turbidity units (Culp, 1977).

The factors controlling the filter run are numerous- raw water quality, colour, algae, mixing energy input, media size, filtration rate and type and dose of coagulant. The

success of direct filtration depends on detailed studies of these factors and judicious alterations to increase the floc strength to prevent turbidity breakthrough and floc volume reduction to obtain longer filter runs.

2.4. Performance of Direct Filtration

Filtered water turbidity in the range of 0.04-0.18 NTU is common mostly when raw water turbidity is less than 10 NTU. It is quite likely that higher turbidity raw waters can also be treated in direct filtration mode in places where WHO effluent turbidity of 5 NTU is acceptable. Tate et al. (1977) found that direct filters removed 99 percent of particles in the size range from 2.5 to 150 µm and essentially removes all particles larger than 10 µm.

The AWWA Filtration Committee (1980) found that due to inadequate alum dose in the direct filtration plants, they could not achieve the objective of 5 Hazen units of effluent color. King and Amy (1979) observed 50 percent colour removal, when raw water colour varied between 9-17 APHA units.

Scheuch and Edzwald (1981) reported that trihalomethane precurser removal using cationic polyelectrolytes was approximately 40 percent. Monscvitz et al. (1978) found an average plankton removal efficiency of 87 percent by direct filtration.

The AWWA Filtration Committee (1980) observed 98 percent virus removal by direct filtration when compared with 99 percent removal by conventional sedimentation-filtration mode. McCormic and King (1982) found that a filtered water

turbidity of 0.1 NTU resulted in complete removal of algae and coliform bacteria. King and Amy (1979) observed excellent coliform removal when raw water coliform count varied between 3-350-126000 per 100 ml. When virus and bacterial removal are concerned, both conventional treatment and direct filtration modes demand disinfection.

2.5. Advantages and Limitations of Direct Filtration

2.5.1. Advantages of Direct Filtration

The main advantage of direct filtration is the potential for capital cost savings upto 30 percent under favourable conditions. This results from the elimination of sludge-collecting equipment, settling basin structures, flocculation equipment and its structure. This cost reduction may make possible the provision of needed filtration for some communities that could not otherwise afford it.

With direct filtration, there may also be a savings of 10-30 percent in chemical costs due to lesser requirement of chemicals. Tate et al. (1977) in their parallel studies noted that direct filtration needed an alum dosage only one fifth of that used in conventional plant, for a filtration rate three times higher (4.1 mm/sec (6 gpm/sq.ft)). Monscvitz et al. (1978) noticed 25 to 40 percent savings in alum dose. Operation and maintenance costs are also reduced because of less equipment requirement. Many water treatment plants of conventional design can operate in direct filtration mode during favourable raw water conditions in order to achieve substantial savings in chemicals and sludge handling costs.

Direct filtration produces less sludge than conventional treatment and the sludge is more dense. Waste soils are also contained in the single filter-backwash water stream, simplifying the waste collection.

Direct filtration, though unable to withstand high shock loadings, can be more effective than conventional treatment in dealing with upsets in coagulation process. Due to short detention time before filtration, it recovers much faster than the conventional mode.

Instances where the present treatment is disinfection only,incorporation of direct filtration tremendously increases the protection of public health.

2.5.2. Limitations of Direct Filtration

The major limitations of this process are less solids holding capacity, shorter filter runs and need for higher backwash water.

The direct filtration process may not be applicable to raw waters with high turbidity, colour, plankton and paper fibre, due to its limited ability to handle high suspended solids.

Although both the conventional and direct filtration modes may produce equal quality of water, the initial turbidity breakthrough is severe for the latter implying the need for close monitoring of turbidity within the media. Because of short time between the application of coagulant and the filtration and the greater load applied to the filters, more operator vigilance is required. The shorter chemical reaction time may be critical in removal of iron

and manganese and after floc formation due to residual aluminum at low temperatures. In the treatment of raw waters containing high concentration of coliform organisms, the reliability of public health protection may be reduced.

Wastewater requirement in direct filtration may be as high as 6 percent as compared with a total 4 percent (2 percent for backwashing plus 2 percent for sludge washing) in a conventional plant treating similar raw water.

As far as our country is concerned, the non-availability of polyelectrolytes suitable for water treatment in our market, is a great constraint. Though certain anionic polyelectrolytes have been developed by NEERI (National Environmental Engineering Research Institute), polyelectrolytes are yet to make their way into our water treatment plants. Consequently, conventional coagulants like alum or iron salts remain to be the choice for direct filtration.

2.6. Batch Coagulation Test (Jar Test)

The jar test has been and is still the most widely used method employed to evaluate the coagulation-flocculation process. If procedures that simulate treatment plant conditions are followed, jar testing can produce reliable and important information quickly and economically, and the data are directly applicable to plant design, modifications, and operation. The procedure offers greater flexibility and economy than the traditional pilot plant test for pretreatment.

In any meaningful testing program there are always imposed certain controls that clarify the effects of varying

parameters on the outcome of the experiment. In jar testing also, care must be exercised in controlling the following variables to get meaningful results: (a) temperature, (b) coagulant solution strength and dosage quantity, (c) pH, (d) sequence, timing and method of addition of reactants (coagulant, coagulant aid), (e) duration and intensity of rapid mix and flocculation, and (f) method of sample withdrawal. In addition, turbidity, color, alkalinity of the raw and treated water should be measured. By controlling the aforementioned variables judiciously, jar test procedure can be used in, though not limited to, the following (Hudson and Wagner, 1981): (a) determining the optimum coagulant dosage and pH, (b) determining the strength of floc, (c) duration and intensity of rapid mix and flocculation and the effect of lag time between the two, (d) evaluating the effect of sludge recycling and the concentration of sludge for recycling, (e) predicting design criteria for in-plant settling, (f) establishing design criteria for tube and tray settlers and (g) evaluating direct filtration possibilities and coagulant dosage. Because of this wide range of application of this technique, it demands great confidence in its applicability.

2.6.1. Apparatus

Camp (1970) used 2-liter beakers as jars and a Phipps and Bird multiple stirrer as a mixing device. He calibrated the set-up with and without stators at 10°C, which make the use of this apparatus easy. His system needs provisions (a) to feed the coagulant dose at a point located

at or close to the hub of the impeller and (b) sampling take off (siphon) for withdraws of the settled water from a specified depth. Hudson (1981) suggested an alternative type of equipment shown in Figure 2.1a to serve these functions. His alternative uses rectangular jars which may be used either with a top-entering stirrer or on a magnetic-drive stirring device. He had also calibrated it (Figure 2.1b). His modified jar test apparatus has the following advantages: (a) the plastic jars are less fragile, (b) no siphon or pipette is needed for sampling, and the sample is withdrawn without disturbing the settling water, (c) the acrylic plastic walls are less heat-conductive than the glass walls of other jars (the wall thickness in the plastic units is about four-fold that of glass beaker which enables the use of it without water bath and no material change in temperature of the water occurs during testing), (d) no need for stators. The results of circular jars may not be comparable with that of plant due to continued rotation (more than a minute) of the water in the jars even on termination of stirring. The use of square jar or baffled jar eliminates this drawback since flow becomes laminar within 30 sec after stopping the agitation and this 20-30 sec period is analogous to the turbulent inlet zone of the settling basins.

2.6.2. Experimental Procedure

The coagulant solution should be added through a dosing funnel or some other injection apparatus to the hub of the impeller during high-speed mixing. It should also be applied under controlled flow rate than dumped on

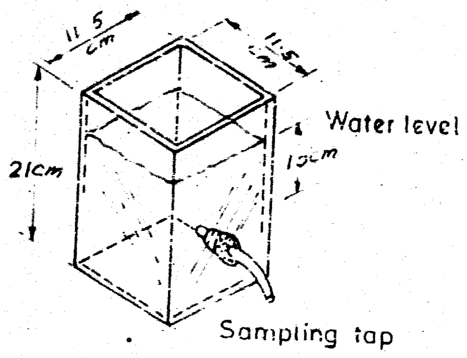

Fig. 2.1a. Two Liter Jar for Bench Scale Testing.

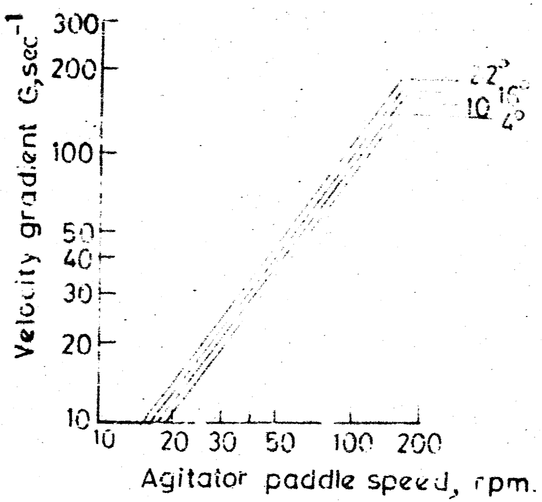

Fig. 2.1b. Velocity Gradient vs. RPM for a Two Liter Square Jar.

(Hudson, 1981)

the water surface. A 2-3 sec dosing duration is desirable and may be accomplished by blowing or gravity flow of the coagulant through a pipette. This allows the coagulant to dose the jar contents as uniformly as possible. If necessary, the dosing tube can be flushed with small quantity of water. For best results, flocculation should follow immediately after the flash mix-time period. During flocculation, observations may be noted on the time of floc appearance as well as color, consistency and estimated size (mm) of the floc particles in each jar. While withdrawing the samples, initial 10 ml should be used to flush-out the sampling tube, and the remaining should be used for analysis (Hudson, 1981).

2.6.3. Modified Jar Test for Direct Filtration

Wagner and Hudson (1982) suggested standard laboratory filter paper (Whatman No. 40, Whatman, Ltd., England) for supplimenting the jar test, to evaluate the feasibility of direct filtration process with low coagulant dosages. The objective is to obtain a filtered water that will meet the applicable standards (WHO International Drinking Water Standards (1971): 5 units each for turbidity and colour; Government of India Drinking Water Standards (Manual on Water Supply and Treatment, 1976): 2.5 units for turbidity and 5 units for colour) and at the same time to establish minimum coagulant and polymer doses. To determine the dosage a sample from each jar or batch that has been subjected to a specific treatment is filtered through standard laboratory filter paper. Fresh filter paper should be used for each jar. The first portion of the filtrate

should be discarded and the balance used for measuring filtered water turbidity. The authors have found this method to give good replication of water quality results in the plant. It does nothing, however, to determine the relative lengths of filter run. That can be determined only by full-scale operation or pilot plant testing of filters. Trials with this bench-scale procedure sort out the variables of best coagulant, most effective polymer, optimum dosages, sequence of application, and stirring intensities and time. If the results of the bench-scale testing are good, then pilot plant tests will be necessary to determine the plant filter design parameters. The equipments, chemicals, and glassware that are necessary to perform the bench scale testing are available in almost all the treatment plant laboratories.

Wagner and Hudson (1982) tested different waters to evaluate the applicability of direct filtration process at different parts of the world. They used the modified jar test for direct filtration (with filter paper) for preliminary investigation which was followed by pilot plant studies. Only at one place (Skinner Water Treatment Plant, U.S.) both bench-scale and pilot tests were followed by plant performance. They found that plant almost always would outperform the bench-scale results. They found, out of their field experience, that the modified jar test to be very much dependable and useful in the initial screening of coagulant doses for direct filtration. In Table 2.1, their experimental

Comparison of Jar Test, Pilot Plant and Plant Performance for Direct Filtration
(Adapted from Wagner and Hudson, 1982)

Place	Turbidity, NTU				Dose, mg/l				Filtration Rate, mm/s (gpm/ft^2)	Filter Run, hr	Terminal Head Loss, m	Number Runs
	Raw Water	Jar Test	Pilot Filter	Plant Filter	Alum	Iron	Lime	Polymer				
Skinner Water Treatment Plant, California, U.S.	2.1	0.33			3.0			0.50				
	2.1	0.30			3.0			0.75				
		0.41				2.0		0.50				
		0.26				2.0		0.75				
			0.22	0.20	3.0			0.50				
			0.27	0.25	2.5			0.25				
			0.27	0.23	2.5			0.40				
	2.1		0.30	0.25	2.0			0.30				
Guam	14.0			<1	25.0		2.0					
	14.0		0.62		3.0			1.50	1 (2)	18	1.7	1
			0.41		3.0			1.50	1 (2)	18	1.2	1
		0.60			5.0			0.80				
		0.40			2.5			1.50				
Brasilia, Brazil	12.0	0.95			3.0							
		0.40			3.0		1.0					
		0.61			2.5		0.2					
		0.82			2.5		0.8					
		1.00			2.0							
	25.0	20.00										
	12.0		0.32		4.0				5 (7.8)	15	1.2	13
	25.0		0.55		3.0		1.0		5 (7.8)	15	1.2	7
	45.0		0.65		4.5		1.0	0.5	5 (7.8)	15	1.2	11

Note: At Skinner Water Treatment Plant, U.S., the plant filters were operated at 7 mm/s and pilot filters were operated at 10 mm/s.

results at three places are shown. A close look at this table confirms the utility of the jar test procedure.

2.7. Filterability Number

2.7.1. Filterability

Filterability is an interactive property, expressing a relationship between a suspension to be filtered and the media which will filter it. It must take into account the quality of filtrate, and the degree of clogging which gives rise to a reduction in permeability, or increase in head loss. A number of measures of filterability has been proposed, using filter paper, woven micromesh or lint pads, or membrane filters, which have applications where these materials represent, or are identical to, the filter media to be used. However, none of them is representative of porous granular filter media and consequently, they are not applicable to deep bed filtration. A better approach to filterability was made by Cleasby in 1969. But its complexity of the methodology does not command itself and full depth filter columns could just as well be used (Ives, 1978).

2.7.2. Filterability Number

Ives (1978) developed a simple, small scale test of filterability. His filterability index called Filterability Number is given by

$$F = \frac{HC}{vC_o t}$$

where, H is the head loss (water gauge),

C is the average filtrate quality,

C_o is the inlet suspension quality,

v is the approach velocity (volumetric flow rate per unit face area)

and t is the time of the filter run.

F is dimensionless and C/C_o is a ratio so that any units of quality can be used (e.g., turbidity, Fe content, coliform number). This number includes the major parameters of deep bed filtration; inlet and filtrate concentrations, i.e., clarification capacity; head loss per unit time, i.e., clogging characteristics; flow rate, which greatly affects filter economy.

For good filtration, i.e., a good filterability, the numerator should be low, with low head loss (clogging), and low filtrate concentration. Also, the denominator should be high, with a high flow rate, accepting high inlet concentration during a long time of operation. Consequently, a good filterability, is expressed by a low Filterability Number. No particular significance can be attached to the actual numerical value of F, but relative values of F indicate relative filterabilities.

Though this test is not a design tool for engineers, intelligent use of the Filterability Number test will enable rapid screening of various pretreatments like choice and dose of coagulant, media and flow rates. Thus it reduces the number of tests on deep experimental columns or pilot plants. In case of plant operation, this test can supplement the routine jar-testing. When raw water quality is good enough for the by-passing of flocculation-clarifiers,

i.e., direct filtration, such condition can be checked by filterability tests. Its simplicity and effectiveness makes it a useful teaching aid in laboratories.

2.7.3. Theoretical Considerations Concerning the Filterability Number

A mathematical model of the ratio of specific surface of a clogged filter (S) to that of the clean filter (S_o) is given by (Ives, 1975):

$$\frac{S}{S_o} = \left(1 + \frac{\beta\sigma}{\varepsilon}\right)^x \left(1 - \frac{\sigma}{\varepsilon}\right)^y$$

where, β is a shape constant,

ε is filter porosity (clean),

σ is specific deposit (volume deposit/unit bed volume),

and x, y-empirically determined exponents.

For most practical systems $x = y = 1$.

Using the Kozeny equation for the hydraulic gradient

$$\frac{\partial H/\partial L}{(\partial H/\partial L)_o} = \left(\frac{\varepsilon}{\varepsilon - \sigma}\right)\left(1 + \frac{\beta\sigma}{\varepsilon}\right)^2 \left(1 - \frac{\sigma}{\varepsilon}\right)^2$$

where $(\partial H/\partial L)_o$ is the hydraulic gradient through the clean filter (at time $t = 0$).

Expanding the brackets of the right hand side

$$\frac{\partial H/\partial L}{(\partial H/\partial L)_o} = 1+(2\beta - 1)\frac{\sigma}{\varepsilon} + (\beta^2 - 2\beta)\frac{\sigma^2}{\varepsilon^2} - \beta^2\frac{\sigma^3}{\varepsilon^3}$$

$$\frac{\partial H}{\partial L} = \left(\frac{\partial H}{\partial L}\right)_o + \left(\frac{2\beta - 1}{\varepsilon}\right)\left(\frac{\partial H}{\partial L}\right)_o \sigma + \left(\frac{\beta^2 - 2\beta}{\varepsilon^2}\right)\left(\frac{\partial H}{\partial L}\right)_o \sigma^2$$
$$- \frac{\beta^2}{\varepsilon^3}\left(\frac{\partial H}{\partial L}\right)_o \sigma^3$$

$$\frac{\partial H}{\partial L} = \left(\frac{\partial H}{\partial L}\right)_o + k_1\sigma + k_2\sigma^2 - k_3\sigma^3$$

In the early stages of filtration $\sigma << 1$, therefore neglecting terms of σ^2 and σ^3

$$\frac{\partial H}{\partial L} = \left(\frac{\partial H}{\partial L}\right)_o + k_1 \sigma$$

Experimentally, this is a well known result.

Integrating with respect to L

$$H = H_o + k_1 \int_o^L \sigma \, dL$$

Using the continuity equation

$$- \frac{\partial C}{\partial L} = \frac{1}{V} \frac{\partial \sigma}{\partial t}$$

where C is the concentration of suspension flowing through the pores, and V is the approach velocity

$$\int_o^\sigma d\sigma = V \int_o^t - \frac{\partial C}{\partial L} dt$$

In finite difference terms $- \frac{\partial C}{\partial L} = \frac{C_o - C}{\delta L}$

If δL is a layer at the inlet face of the filter, then C_o is the inlet concentration.

$$\sigma = V \left(\frac{C_o - C}{\delta L}\right) t$$

where C is the mean concentration leaving δL during t.

$$H = H_o + k_1 Vt \int_o^L \left(\frac{C_o - C}{\delta L}\right) dL$$

$$H = H_o + k_1 V(C_o - C)t$$

This is also a well known result experimentally, that for filter clogging within the pores the head loss rises linearly with time, for the earlier part of the filter run. If the change in head loss $H - H_o = \Delta H$

$$\Delta H = k_1 V(C_o - C)t$$

$$k_1 = \frac{\Delta H}{V(C_o - C)t}$$

For k_1 to maintain its dimensionless characteristics, C and C_o must be dimensionless, i.e. concentrations of suspensions measured in vol/vol (or mass/mass) terms.

The coefficient k_1 could be regarded as an index of filterability, however it suffers a poor sensitivity as $C \to 0$, and there are practical problems in expressing C_o and C in dimensionless terms. The ratio C/C_o has better sensitivity to small values and changes in C_1 and it solves the problems of expressing concentration in any particular units.

Consequently $K_1 = \frac{\Delta H}{V(C_o - C)t}$ was modified to

$$F = \frac{HC}{V\ C_o\ t}$$

In effect, F expresses the output of the filter H and C to the input: total load of suspension applied per unit face area of the filter $V\ C_o\ t$.

3. SCOPE OF THE INVESTIGATION

The search for control techniques that could quickly and easily enable the plant operator to find the optimum combination of chemicals for effective coagulation and filtration has gone on for many years. Among the techniques mentioned by Hannah et al. (1967) were the jar test, zeta potential, colloid titration, the coagulant control center, turbidity monitoring, cotton plug filters (used by Baylis in Chicago in the 1940s and 1950s), a silting index test, and particle counting. Use of pilot filters was recently recommended by Trussel et al. (1980) for controlling the direct filtration process. Kreissl et al. (1968) reported that the optimum chemical dosage could be found using pilot filters for systems that excluded flocculation and sedimentation. In spite of the efforts of many engineers, scientists, and others, no cheap and easily used method of controlling coagulation has been found (Logsdon and Fox, 1982). Jar test is the most common, simple, and may be the only test carried out in most water treatment plants for selection of coagulant dosage. For direct filtration, however, the actual doses needed have been reported to be much lesser than that obtained using the conventional jar test. Moreover, jar test as such cannot provide information regarding the filterability or head loss development. Only time-consuming column studies or pilot plant studies can provide those details. The missing link between the jar test and the column test seems to be a filterability test.

It is felt that this gap can be filled by Hudson's modified jar test for direct filtration which incorporates the filterability aspect and Ives' filterability number test. In the present investigation these two techniques along with the conventional jar test are compared with bench-scale column studies to find out whether they can be used in the plant laboratories for selection of alum dose for direct filtration. Efforts are directed towards obtaining correlations between the optimum doses selected by these techniques and the optimum dose obtained from column studies. An attempt is made to study the effects of flocculation time on direct filtration process.

4. MATERIALS AND METHODS

4.1. Materials

4.1.1. Media

Raw river sand used for preparation of the filter beds in the Kanpur Water Treatment Works was utilized to prepare the sand media for the present study. Giridih bituminous coal (GBC) obtained through the Water Treatment Division, NEERI, Nagpur was used in dual-media studies. The geometric mean sizes of sand and coal were 0.6 mm and 1.7 mm, respectively.

4.1.2. Water

The water from the Ganga Canal (near the Panki Thermal Power Station), Kanpur, was used for all the studies. A stock turbid suspension was prepared by allowing the canal water to settle for 1/2 hr. The supernatant was then discarded and the settled particles were collected and used to make up the turbidity of the canal water sample to required level before each experimentation.

4.1.3. Chemicals

Alum or aluminum sulphate $Al_2(SO_4)_3.16H_2O$, Laboratory Reagent grade supplied by Sarabhai M. Chemicals, Baroda was used as coagulant throughout the study.

4.2. Methods

4.2.1. Canal Water Analysis

The canal water samples were analysed for various parameters of interest to the present study and tabulated (Table 4.1). Turbidity was measured by a Hach

Table 4.1

Analysis of Ganga Canal Water

1.	Turbidity	9-84 NTU
2.	pH	7.9-8.5
3.	Total hardness	80.8-138.61 mg/l as $CaCO_3$
4.	Alkalinity	140-220 mg/l as $CaCO_3$
5.	Acidity	8-40 mg/l as $CaCO_3$
6.	Specific conductivity	180-266 μsiemens/cm

turbidimeter (Model 2100A). Since the turbidity standards supplied by the manufacturer were found aged, new stands were prepared as per the procedure outlined in the Standard Methods (1976). Conductivity was measured by a conductivity bridge (Toshniwal) and pH by a pH meter (Systronics) and other parameters, viz., hardness, acidity, and alkalinity by the procedures outlined in the Standard Methods (1976).

4.2.2. Batch Coagulation Test (Jar Test)

The objectives of this phase were

(i) to find out the optimum alum dose for direct filtration process as per Hudson's (1982) modified procedure,

(ii) to find out the optimum alum dose for conventional mode with settling (conventional jar test), and

(iii) to screen the doses for the next phase, viz., filterability tests.

A six-place multiple-stirrer jar test apparatus (Phipps and Bird, Richmond, Va.) was used with Hudson's (1981) modified jars (Figure 2.1a). The turbidity ranges of 10, 20, and 30 NTU were studied. Alum dosages 0 (control), 2, 3, 4, 5, 7.5, 10, 12.5, 15, 17.5 and 20 mg/l were used for direct filtration and conventional modes, and further higher dosages of 25, 30, 40 and 50 mg/l for conventional mode alone.

The following procedure was adopted for batch coagulation studies:

(i) The canal water samples, made upto the required turbidity level, were placed in jars (2000 ml).

(ii) To each jar, while mixing @ 100 rpm, alum (5 g/l solution) was added according to preselected dosages.

(iii) The contents were mixed for 1 min @ 100 rpm (G-110 sec^{-1}), followed by 20 rpm (G-15 sec^{-1}) for 20 min, and 20 min of quiescent settling.

(iv) Samples were withdrawn after flash mix, during flocculation at 5, 10, 15, 20 min and filtered through Whatman No. 40 filter paper to simulate direct filtration mode with or without flocculation. Initial portion of filtrate (10 ml) was discarded and the remainder was used for turbidity analysis. Sample was also withdrawn after the 20 min settling period and a portion of it was filtered to simulate conventional settling-filtration mode and both the unfiltered and filtered portions were analysed for turbidity.

4.2.3. Filterability Number Test

The objective of this phase was to select the optimum alum doses for direct filtration using Ives' Filterability Number test for single-media sand and coal-sand dual-media for the same raw water turbidity ranges used in the previous phase.

The filterability tests were performed using the filterability apparatus, details of which are given in Figure 4.1. The procedure adopted by Ives (1978) and used in this study was as follows:

(i) The empty apparatus was filled with clean water to establish the manometers.

(ii) Since filterability is sensitive to porosity, the weight of sand to provide a porosity of 0.4 for a depth of 4 cm was estimated and used in all experiments in the case of single sand medium.

(iii) The sand was wetted thoroughly and the apparatus was reverse filled to expel air from the medium and the apparatus, until the water had risen to the base of the inlet separatory funnel. The outlet was shut off and by tapping the filter unit the surface of the medium was levelled and consolidated to the correct depth of 4 cm.

(iv) One litre of sample pretreated to the desired level (flashmix with or without flocculation) was fed to the filter unit through the separatory funnel and the flow was maintained at 9.8 $m^3/m^2/h$ (4 gpm/ft^2). The time taken for filtration and the head loss at

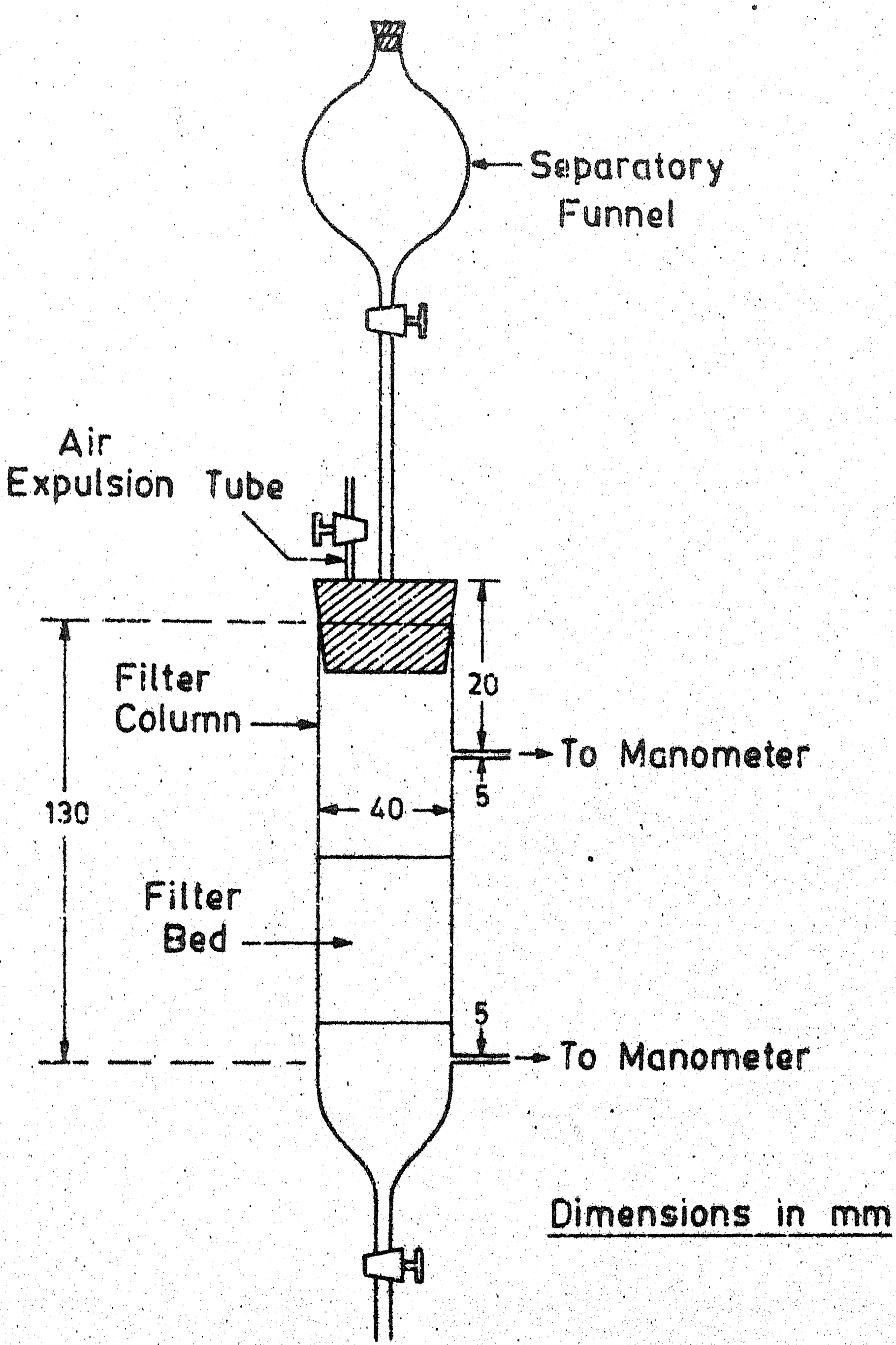

Fig. 4.1. Experimental Setup for Determination of Filterability Number .

the end of the run were noted. Turbidity of feed suspension and filtered water were measured. The filterability number was calculated using Ives' formula.

The same procedure was followed for dual-media. The depth of coal (2.4 cm) and sand (1.6 cm) were in the same proportion, as in the subsequent column studies. The porosity of coal and sand were 0.6 and 0.4, respectively. For dual-media, only one range of turbidity (with flash mix alone), viz., 30 NTU was used.

Hudson's modified jar tests were repeated along with filterability tests.

4.2.4. Column Studies

The objective of this phase was to select the optimum alum dose for each turbidity range and to compare the values with those obtained from the jar tests and the filterability number tests.

The column studies were performed using a 1.1 cm glass tube which had provision to measure the total head loss across the bed. This set-up was resorted to for a good control over the process throughout the run and due to practical difficulties to fabricate a continuous system. A total media depth of 50 cm was provided. In dual-media studies, the depths of coal (porosity: 0.6) and sand (porosity: 0.4) were 30 cm and 20 cm, respectively. For dual-media only, 30 NTU raw water turbidity was used. For single sand medium, turbidity ranges of 10, 20 and 30 NTU were employed. Alum dosages of 5, 7.5, 10, 12.5, 15, 17.5,

and 20 mg/l were used. Flash mixed suspension (1 l) was fed to the column from a separatory funnel at 1 hr intervals. All the runs were performed for 4 hr at a flow rate of 9.8 $m^3/m^2/hr$ (4 gpm/ft^2). The head loss measurement and effluent sample collection for turbidity were done at $\frac{1}{2}$ hr intervals.

5. RESULTS AND DISCUSSION

Results of all experiments are presented in graphical or tabular form. In order to facilitate presentation, a discussion of the results follows each phase of the experimental work. For the most part, only typical results are shown and discussed. Data on laboratory techniques for alum dose selection are presented in the earlier section. This is followed by data on bench-scale filter column studies together with relevant data from the previous section.

5.1. Jar Test

Data for conventional jar test (coagulation-settling), conventional jar test with filtration of the supernatant following settling to simulate coagulation-settling-filtration as suggested by Hudson (1981), and Hudson's modified jar test for direct filtration with varying flocculation times are presented in Tables 5.1 to 5.3. Three raw water turbidity levels were employed, viz., 10, 20 and 30 NTU.

Analyses of the data in Tables 5.1 to 5.3 indicate that, in general, (a) only the alum doses of 7.5 mg/l and above produced favourable filtrate quality (around 1 NTU or less), (b) a short flocculation time of 5 min marginally aided the flash mix, though for 10 NTU turbidity level none of the flocculation durations improved the filtrate quality indicating that flocculation could be dispenced with for this turbidity level, and (c) for conventional jar test (coagulation-settling), optimum dose was 30 mg/l for all the three turbidity levels.

Table 5.1

Jar Test Data for 30 NTU Turbidity Raw Water

Alum Dose, mg/l	Filtrate Turbidity, NTU					Turbidity After Settling, NTU	
	After Flash Mix[a]	After Flocculation[b]					
		5 min	10 min	15 min	20 min	Unfiltered[c]	Filtered[d]
0.0	2.70	3.00	2.80	3.20	3.70	20.00	3.90
2.0	3.80	2.40	4.00	2.40	3.40	16.00	3.60
3.0	2.00	1.40	3.60	1.80	2.80	15.00	2.10
4.0	2.20	1.50	1.80	2.20	2.60	14.00	2.20
5.0	1.40	0.60	0.98	0.63	1.80	14.00	1.80
7.5	0.45	0.55	0.52	0.52	0.54	12.00	0.36
10.0	0.75	0.48	1.10	0.44	0.68	6.50	0.74
12.5	0.52	0.51	0.67	0.45	0.55	3.60	0.34
15.0	0.40	0.32	0.42	0.37	0.30	2.70	0.42
17.5	0.28	0.32	0.40	0.23	0.28	2.10	0.27
20.0	0.32	0.27	0.31	0.42	0.26	1.90	0.38
25.0	-	-	-	-	-	1.30	0.55
30.0	-	-	-	-	-	1.10	0.45
40.0	-	-	-	-	-	0.92	0.52
50.0	-	-	-	-	-	0.82	0.47

a - direct filtration without flocculation;

b - direct filtration with different flocculation times;

c - conventional jar test;

d - conventional jar test simulating filtration.

Table 5.2

Jar Test Data for 20 NTU Turbidity Raw Water

Alum Dose, mg/l	Filtrate Turbidity, NTU					Turbidity After Settling, NTU	
	After Flash Mix[a]	After Flocculation[b]					
		5 min	10 min	15 min	20 min	Unfiltered[c]	Filtered[d]
0.0	5.70	7.40	6.80	5.10	7.20	18.00	8.20
2.0	5.90	7.20	7.10	7.70	7.60	18.00	7.00
3.0	4.60	6.30	5.80	6.70	5.70	17.00	7.60
4.0	3.60	4.70	3.80	3.30	4.80	17.00	5.60
5.0	3.00	4.00	4.30	4.00	4.60	16.00	4.50
7.5	1.50	1.30	0.67	0.77	0.65	16.00	0.68
10.0	1.60	0.65	2.00	0.57	0.53	10.00	0.66
12.5	0.62	0.57	0.70	0.48	0.59	6.80	0.51
15.0	0.38	0.38	0.67	0.45	0.42	2.30	0.37
17.5	0.32	0.37	0.52	0.28	0.46	1.60	0.32
20.0	0.37	0.36	0.38	0.33	0.41	1.70	0.49
25.0	-	-	-	-	-	1.30	0.48
30.0	-	-	-	-	-	0.92	0.47
40.0	-	-	-	-	-	0.83	0.62
50.0	-	-	-	-	-	0.77	0.52

a - direct filtration without flocculation;

b - direct filtration with different flocculation times;

c - conventional jar test;

d - conventional jar test simulating filtration.

Table 5.3

Jar Test Data for 10 NTU Turbidity Raw Water

Alum Dose, mg/l	Filtrate Turbidity, NTU					Turbidity After Settling, NTU	
	After Flash Mix[a]	After Flocculation[b]					
		5 min	10 min	15 min	20 min	Unfiltered[c]	Filtered[d]
0.0	3.70	3.60	4.20	3.60	4.00	7.50	2.90
2.0	3.20	3.10	3.40	3.30	3.40	7.70	3.90
3.0	1.50	2.00	1.70	2.00	1.80	4.30	1.80
4.0	1.70	1.60	1.70	1.70	1.60	4.40	2.20
5.0	1.60	1.40	1.50	1.60	1.70	4.90	1.50
7.5	1.10	1.10	1.30	0.69	0.64	5.00	0.64
10.0	0.50	0.54	0.39	0.60	0.52	4.40	0.41
12.5	0.40	0.41	0.51	0.42	0.55	2.20	0.52
15.0	0.47	0.55	0.45	0.53	0.52	1.80	0.54
17.5	0.49	0.50	0.48	0.54	0.51	1.30	0.47
20.0	0.48	0.47	0.48	0.39	0.48	1.30	0.57
25.0	-	-	-	-	-	0.91	0.60
30.0	-	-	-	-	-	0.74	0.56
40.0	-	-	-	-	-	0.78	0.53
50.0	-	-	-	-	-	0.70	0.57

a - direct filtration without flocculation;

b - direct filtration with different flocculation times;

c - conventional jar test;

d - conventional jar test simulation filtration.

On the basis of above observations, it was decided to employ alum doses of 3 mg/l and above in the Ives' filterability number tests for direct filtration. A flocculation duration of 5 min following flash mix was also included.

5.2. Filterability Number Test

Hudson's modified jar test for direct filtration was repeated with each filterability number test. These filtrate turbidity values and filterability numbers (flash mix with and without 5 min flocculation) are presented in Table 5.4 to 5.6. The following general trends are observed from the data: (a) the filterability numbers declined in magnitude upto the highest alum dose studied indicating improved filterability characteristics of the suspension with increasing alum dose, and (b) 5 min flocculation following flash mix aided filterability.

5.3. Column Studies

Performance (effluent turbidity and head loss) of the bench-scale filter column study using the direct filtration mode are shown in Appendix Tables A1 to A4. Due to limitations of the set-up employed, the effect of short flocculation time (5 min) following flash mix could not be studied in this phase.

5.3.1. Single-Media Sand

The average filtrate turbidity was obtained in most of the runs at the third hour. These values and the corresponding head losses against alum doses are presented in Figures 5.1 to 5.3 for raw water turbidities of 30, 20 and 10 NTU, respectively. Jar test data (direct

Table 5.4

Filterability Number (Single-Media Sand) and Hudson's Modified Jar Test Data for 30 NTU Turbidity Raw Water

Alum Dose, mg/l	Flash Mix		Flash Mix + 5 min Flocculation	
	Filterability Number	Filtrate Turbidity (Hudson), NTU	Filterability Number	Filtrate Turbidity (Hudson), NTU
5.0	28.88×10^{-3}	3.20 (1.40)	21.47×10^{-3}	1.30 (0.60)
7.5	14.77×10^{-3}	0.65 (0.45)	12.27×10^{-3}	1.20 (0.55)
10.0	7.33×10^{-3}	0.51 (0.75)	8.45×10^{-3}	0.61 (0.48)
12.5	5.88×10^{-3}	0.60 (0.52)	4.44×10^{-3}	0.60 (0.51)
15.0	2.05×10^{-3}	0.40 (0.40)	1.28×10^{-3}	0.29 (0.32)
17.5	1.54×10^{-3}	0.31 (0.28)	0.89×10^{-3}	0.39 (0.32)
20.0	1.28×10^{-3}	0.41 (0.32)	1.20×10^{-3}	0.38 (0.27)

Note: Filtrate turbidity values of Hudson's modified jar test for direct filtration, performed in the previous phase, are shown in parentheses.

Table 5.5

Filterability Number (Single-Media Sand) and Hudson's Modified Jar Test Data for 20 NTU Turbidity Raw Water

Alum Dose, mg/l	Flash Mix		Flash Mix + 5 min Flocculation	
	Filterability Number	Filtrate Turbidity (Hudson), NTU	Filterability number	Filtrate Turbidity (Hudson), NTU
5.0	27.81×10^{-3}	1.50 (3.00)	25.48×10^{-3}	2.00 (4.00)
7.5	25.96×10^{-3}	2.10 (1.50)	11.23×10^{-3}	0.77 (1.30)
10.0	10.82×10^{-3}	0.56 (1.60)	12.47×10^{-3}	0.65 (0.65)
12.5	4.54×10^{-3}	0.43 (0.62)	8.33×10^{-3}	0.57 (0.57)
15.0	5.61×10^{-3}	0.50 (0.38)	4.52×10^{-3}	0.46 (0.38)
17.5	3.96×10^{-3}	0.53 (0.32)	3.20×10^{-3}	0.43 (0.37)
20.0	3.29×10^{-3}	0.41 (0.37)	3.17×10^{-3}	0.51 (0.36)

Note: Filtrate turbidity values of Hudson's modified jar test for direct filtration, performed in the previous phase, are shown in parentheses.

Table 5.6

Filterability Number (Single-Media Sand) and Hudson's Modified Jar Test Data for 10 NTU Turbidity Raw Water

Alum Dose, mg/l	Flash Mix		Flash Mix + 5 min Flocculation	
	Filterability Number	Filtrate Turbidity (Hudson), NTU	Filterability Number	Filtrate Turbidity (Hudson), NTU
5.0	32.64×10^{-3}	3.00 (1.60)	26.07×10^{-3}	3.20 (1.40)
7.5	21.93×10^{-3}	2.20 (1.10)	24.33×10^{-3}	2.20 (1.10)
10.0	20.68×10^{-3}	1.20 (0.50)	11.99×10^{-3}	0.65 (0.54)
12.5	8.62×10^{-3}	0.52 (0.40)	5.75×10^{-3}	0.47 (0.41)
15.0	7.65×10^{-3}	0.46 (0.47)	5.29×10^{-3}	0.57 (0.55)
17.5	6.35×10^{-3}	0.47 (0.49)	2.86×10^{-3}	0.41 (0.50)
20.0	4.43×10^{-3}	0.29 (0.48)	22.83×10^{-3}	0.29 (0.47)

Note: Filtrate turbidity values of Hudson's modified jar test for direct filtration, performed in the previous phase, are shown in parentheses.

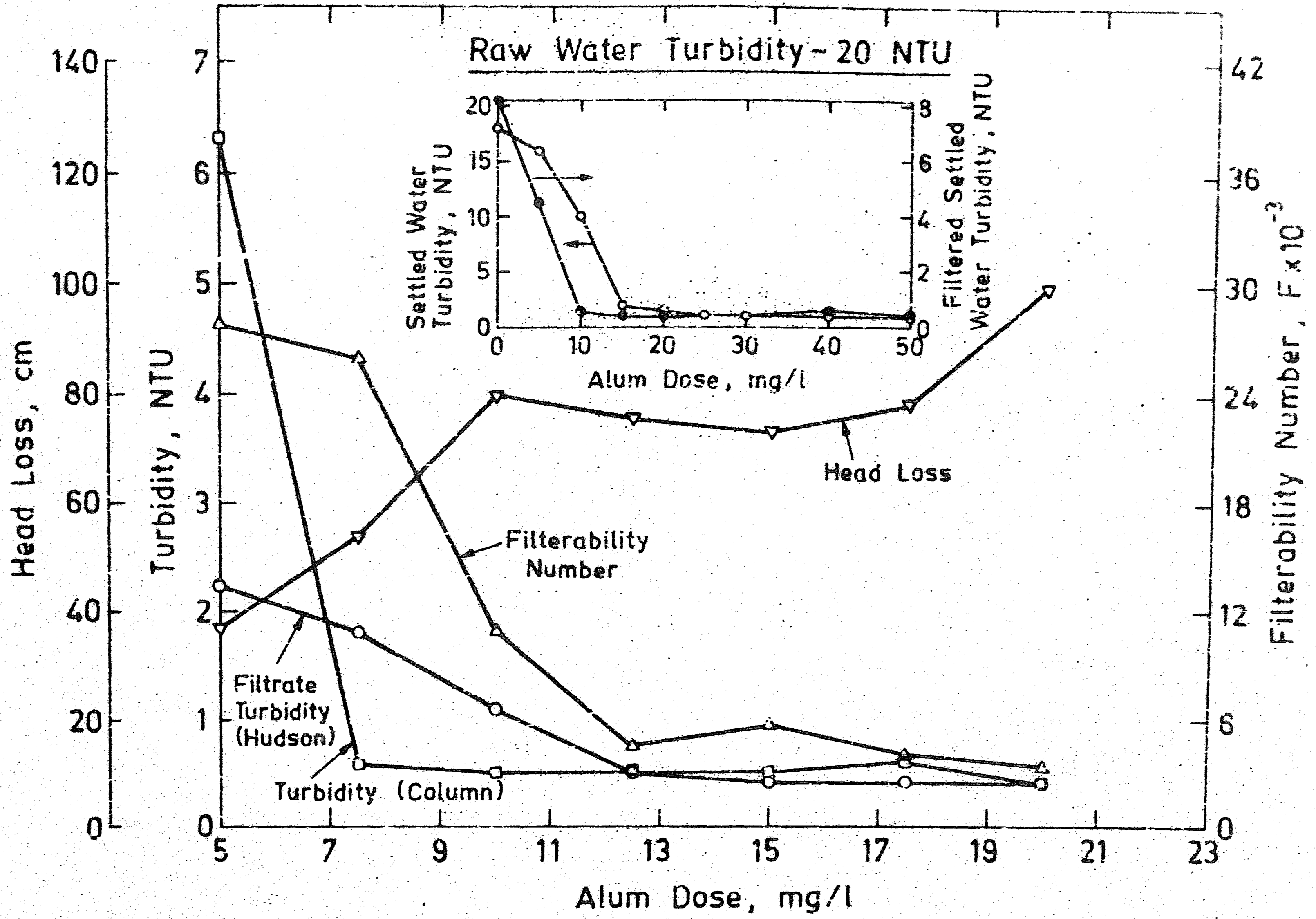

Fig. 5.2. Sand Filter Column Performance vs. Filterability Number and Jar Tests Data for 20 NTU Raw Water Turbidity.

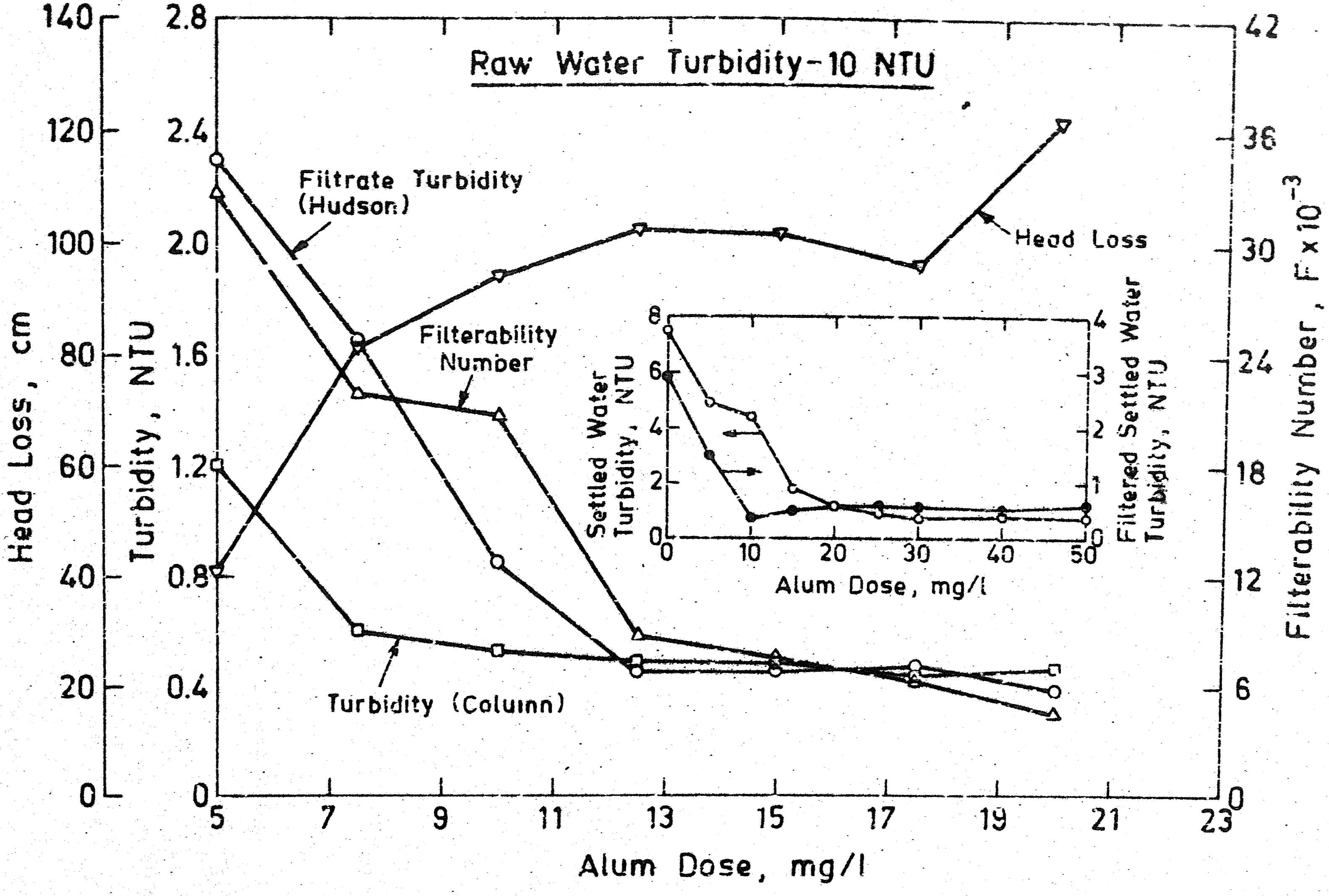

Fig. 5.3. Sand Filter Column Performance vs. Filterability Number and Jar Tests Data for 10 NTU Raw Water Turbidity.

filtration mode) and filterability numbers for the corresponding alum doses are also included in the figures to facilitate comparison. Since Hudson's modified jar tests for direct filtration were repeated for each alum dose, the average filtrate turbidity values were plotted. The inset in each figure shows data on conventional jar test (coagulation-settling) and conventional jar test with filtration of the supernatant following settling to simulate coagulation-settling-filtration as suggested by Hudson (1981). The optimum alum doses obtained using different techniques were selected from Figures 5.1 to 5.3 and are shown in Table 5.7 with the corresponding turbidity values.

From the consolidated Table 5.7, it is observed, in general, that (a) both Hudson's modified jar test for direct filtration and Ives' filterability number test are equally effective in predicting optimum alum dose for direct filtration, (b) Hudson's modified jar test filtrate turbidity can well indicate column effluent turbidity, and (c) direct filtration can produce filtered water of quality comparable to that from the conventional settling-filtration mode (as predicted by the jar test).

It is evident from Table 5.7 that for low raw water turbidity values (10-30 NTU) suitable for direct filtration, conventional jar test (coagulation-settling) alum doses do not correlate well with those observed optimum from bench-scale column studies. However, doses in the range 80 to 83 percent of those predicted by Hudson's modified jar test for

Table 5.7

Alum Doses for Single-Media Sand Direct Filtration

Technique	Raw Water Turbidity					
	30 NTU		20 NTU		10 NTU	
	Optimum Dose, mg/l	Turbidity, NTU	Optimum Dose, mg/l	Turbidity, NTU	Optimum Dose, mg/l	Turbidity NTU
Column studies	12.5	0.37	10.0	0.50	10.0	0.53
Hudson's modified jar test for direct filtration	15.0	0.40	12.5	0.43	12.5	0.46
Ives' filterability number	15.0	-	12.5	-	12.5	-
Conventional jar test	30.0	1.10 (0.45)	30.0	0.92 (0.47)	30.0	0.74 (0.56

Note: Turbidity values for conventional jar test are those following settling. Turbidity values of the filtered (Whatman No. 40) water following settling are shown in parentheses.

direct filtration and Ives' filterability number test are suitable.

5.3.2. Dual-Media: Coal-Sand

Ives' filterability numbers for dual-media (2.4 cm coal and 1.6 cm sand) are presented in Table 5.8. Hudson's modified jar test for direct filtration was repeated with each filterability number test. In bench-scale column studies, the average filtrate turbidity was obtained at $3\frac{1}{2}$ hr. Figure 5.4 shows the data on bench-scale dual-media column study and jar tests as well as filterability numbers for 30 NTU raw water turbidity.

The optimum alum dose observed from the column study was 15 mg/l with an average effluent turbidity of 0.33 NTU and 17.5 mg/l dose was predicted by both Hudson's modified jar test for direct filtration as well as Ives' filterability number test which is 86 percent of the dose observed in the column study. Hudson's modified jar test could also predict well the effluent turbidity. As before, the dose predicted by the conventional jar test did not correlate well with the dose observed optimum from column study.

Table 5.8

Filterability Number (Coal-Sand Dual-Media) and Hudson's Modified Jar Test Data for 30 NTU Turbidity Raw Water

Alum Dose, mg/l	Flash Mix	
	Filterability Number	Filtrate Turbidity (Hudson), NTU
7.5	12.50×10^{-3}	0.91 (0.45)
10.0	7.97×10^{-3}	0.63 (0.75)
12.5	4.47×10^{-3}	0.45 (0.52)
15.0	3.45×10^{-3}	0.44 (0.40)
17.5	2.42×10^{-3}	0.42 (0.28)
20.0	3.12×10^{-3}	0.51 (0.32)

Note: Filtrate turbidity values of Hudson's modified jar test for direct filtration, performed in the previous phase, are shown in parentheses.

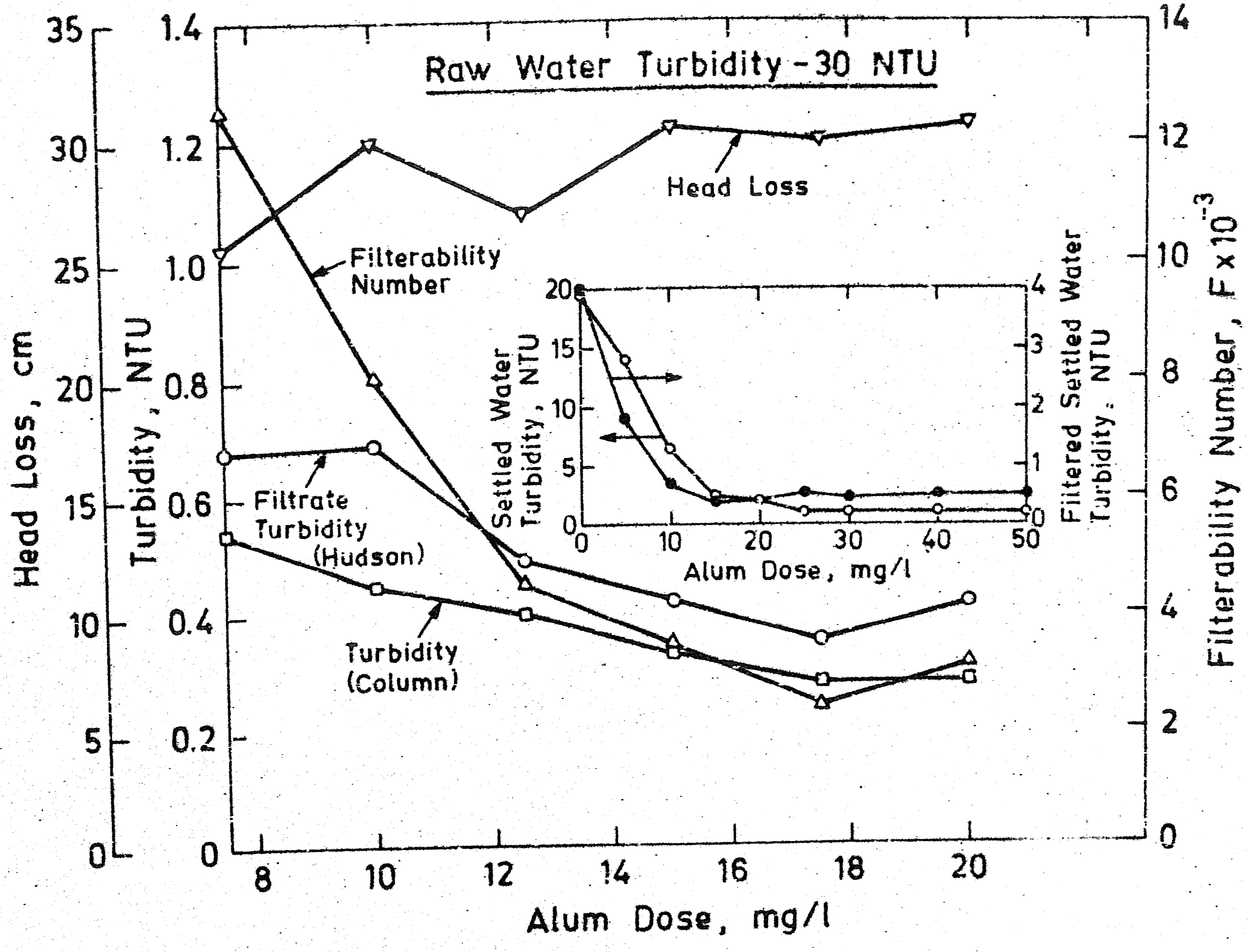

Fig. 5.4. Dual-Media Coal-Sand Filter Column Performance vs. Filterability Number and Jar Tests Data for 30 NTU Raw Water Turbidity.

6. SUMMARY AND CONCLUSIONS

A study was conducted to evaluate laboratory techniques which could help the treatment plant personnel in the selection of optimum alum dose for direct filtration. Two simpler, quick tests, namely, Hudson's modified jar test for direct filtration and Ives' filterability number test were evaluated along with the conventional jar test for a raw water turbidity range of 10-30 NTU. A limited study was undertaken to find the effects of flocculation duration following flash mix on direct filtration. Based on the study, the following conclusions are made:

1. Both Hudson's modified jar test and Ives' filterability number test are effective laboratory techniques in predicting the optimum coagulant dose for both single- and dual-media direct filtration. The optimum dose for direct filtration is about 80 to 85 percent of the optimum dose predicted by these two techniques.
2. Hudson's modified jar test can very well indicate the column effluent turbidity.
3. For low turbidity raw water suitable for direct filtration, the conventional jar test is rather insensitive in predicting the dose for direct filtration.

7. ENGINEERING SIGNIFICANCE AND SUGGESTIONS FOR FUTURE WORK

7.1. Engineering Significance

When raw water quality is favourable, direct filtration is a potentially attractive technology to utilize in developing countries like ours. Whether it is conventional water treatment system with coagulation and settling preceding filtration or direct filtration, at present the water treatment plant personnel have got the conventional jar testing as the only effective technique to control chemical pretreatment of the water. Since conventional jar test doses are usually much higher than that needed for direct filtration, many researchers recommended the time consuming pilot plant testing to control the chemical doses for direct filtration process which may not be practicable in most of the plants. In the present study two simpler laboratory techniques, viz., Hudson's modified jar test for direct filtration and Ives' filterability number test, were evaluated and found to be effective in predicting coagulant dose for direct filtration. Experimental data obtained in the present study established the applicability of these two laboratory techniques.

7.2. Suggestions for Future Work

1. In the present study, the suggested techniques were employed for limited range of raw water turbidities. More experimental work with a wide range of raw water turbidities should be undertaken to support the

present conclusions. Other variables, viz., filtration rate, media size and flash mix duration may also be included.

2. The results of the present study indicated beneficial effect of short flocculation duration. Due to limitations of the bench-scale set-up, effects of flocculation could not be studied further. Future investigation in this direction is recommended.

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APPENDIX

Table A1

Filter Column Performance (Sand) for 30 NTU Raw Water Turbidity at Various Alum Doses at 9.8 $m^3/m^2/hr$ (4 gpm/sq.ft)

Time, hr	Column Effluent Turbidity, NTU							Total Head Loss, cm						
	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l
$\frac{1}{2}$	5.9	4.0	0.71	0.47	0.44	0.53	0.47	30.0	32.3	32.6	9.6	38.2	40.4	37.1
1	5.8	4.0	0.66	0.43	0.43	0.48	0.47	29.4	31.8	34.5	3.0	42.8	45.2	47.0
$1\frac{1}{2}$	5.7	2.6	0.60	0.37	0.43	0.43	0.46	31.7	35.7	40.0	7.9	52.8	62.4	56.6
2	5.6	2.7	0.59	0.37	0.40	0.40	0.43	31.0	35.6	48.8	66.4	61.3	66.8	67.6
$2\frac{1}{2}$	5.3	2.7	0.55	0.39	0.40	0.41	0.45	33.4	38.8	55.8	75.0	76.0	86.9	121.9
3	5.3	3.1	0.68	0.37	0.40	0.43	0.52	32.9	38.6	57.1	83.0	89.0	90.6	134.8
$3\frac{1}{2}$	5.3	2.8	0.54	0.35	0.38	0.42	-	35.4	42.0	69.9	107.5	106.2	112.6	-
4	5.4	3.2	0.45	0.72	0.36	0.42	-	35.4	42.0	73.5	119.0	112.1	125.3	-

Note: The column run with 20 mg/l dose was terminated due to excessive head loss.

Table A2

Filter Column Performance (Sand) for 20 NTU Raw Water Turbidity at Various Alum Doses at 9.8 $m^3/m^2/hr$ (4 gpm/sq.ft)

Time, hr	Column Effluent Turbidity, NTU							Total Head Loss, cm						
	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l
$\frac{1}{2}$	7.3	1.20	0.63	0.80	0.52	0.53	0.54	28.3	32.5	36.8	34.2	38.0	36.3	43.1
1	6.0	1.10	0.61	0.67	0.55	0.55	0.43	32.5	37.2	49.4	39.7	44.6	42.0	52.9
$1\frac{1}{2}$	6.3	1.10	0.56	0.64	0.47	0.50	0.43	32.8	40.9	57.3	52.1	52.6	54.4	62.8
2	6.3	1.10	0.51	0.54	0.46	0.44	0.40	31.8	45.0	63.8	58.5	60.7	62.4	77.3
$2\frac{1}{2}$	5.8	0.63	0.55	0.49	0.47	0.41	0.39	37.1	49.1	72.2	69.9	69.7	68.4	85.6
3	6.3	0.58	0.50	0.50	0.49	0.62	0.40	37.2	54.4	80.3	75.5	73.4	78.2	98.7
$3\frac{1}{2}$	5.2	0.61	0.53	0.47	0.45	0.41	0.41	39.4	61.0	92.5	84.0	85.7	87.7	110.8
4	5.8	0.57	0.49	0.42	0.43	0.38	0.36	39.8	63.5	101.6	96.0	92.0	91.2	114.6

Table A3

Filter Column Performance (Sand) for 10 NTU Raw Water Turbidity at Various Alum Doses at 9.8 $m^3/m^2/hr$ (4 gpm/sq.ft)

Time, hr	Column Effluent Turbidity, NTU							Total Head Loss, cm						
	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l	5 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l
$\frac{1}{2}$	1.8	0.66	0.58	0.54	0.51	0.50	0.53	31.0	39.0	39.9	44.3	43.9	41.8	45.3
1	1.3	0.82	0.55	0.52	0.48	0.49	0.54	33.8	46.7	49.4	54.1	55.4	52.1	58.2
$1\frac{1}{2}$	1.3	0.71	0.54	0.48	0.50	0.53	0.47	35.1	59.8	60.0	71.5	72.9	64.7	77.1
2	1.3	0.55	0.50	0.48	0.47	0.49	0.45	37.2	67.4	68.1	81.0	83.8	73.4	89.9
$2\frac{1}{2}$	1.3	0.57	0.50	0.48	0.46	0.45	0.47	38.8	74.2	79.3	96.6	95.6	90.9	107.0
3	1.2	0.61	0.53	0.49	0.48	0.43	0.47	41.2	81.1	91.4	102.6	101.6	96.0	122.3
$3\frac{1}{2}$	1.5	0.58	0.48	0.47	0.44	0.43	0.52	42.6	91.5	101.7	122.0	121.5	114.0	143.6
4	1.4	0.58	0.52	0.49	0.47	0.44	0.45	43.4	95.4	106.4	112.6	133.3	125.0	148.5

Table A4

Filter Column Performance (Coal-Sand) for 30 NTU Raw Water Turbidity at Various Alum Doses at 9.8 $m^3/m^2/hr$ (4 gpm/sq.ft)

Time, hr	Column Effluent Turbidity, NTU						Total Head Loss, cm					
	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l	7.5 mg/l	10 mg/l	12.5 mg/l	15 mg/l	17.5 mg/l	20 mg/l
$\frac{1}{2}$	0.56	0.43	0.32	0.40	0.28	0.28	17.3	20.0	18.4	20.2	18.8	19.2
1	0.51	0.44	0.35	0.29	0.29	0.31	19.5	22.5	20.2	21.9	20.6	21.3
$1\frac{1}{2}$	0.62	0.44	0.34	0.38	0.30	0.32	21.6	23.5	21.6	23.3	22.4	22.9
2	0.53	0.43	0.37	0.28	0.29	0.33	23.0	24.0	22.5	25.1	25.4	24.3
$2\frac{1}{2}$	0.49	0.36	0.37	0.32	0.30	0.32	21.9	29.2	23.8	27.1	25.5	27.0
3	0.47	0.43	0.39	0.33	0.33	0.29	26.8	30.5	25.0	28.8	26.9	28.7
$3\frac{1}{2}$	0.54	0.45	0.40	0.33	0.28	0.28	25.6	30.1	26.9	30.6	30.0	30.7
4	0.57	0.48	0.37	0.33	0.28	0.29	27.6	32.4	27.7	32.3	32.5	31.9